Predicting Relative-Permeability Curves Directly From Rock Images

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Darcy's law extension for 2-phase flow

"…the obvious futility of attempting to solve these [Navier-Stokes] equations for multiply connected passages composed of the pores of a porous medium has necessitated a direct empirical solution of the problem."

M.Muskat and M.Meres *The flow of heterogeneous fluids through porous media* Physics, 1936

Pore-network model

"The use of high speed computers, such as Illiac, will make possible tests of network model that I could not even consider…"

I.Fatt, *The network model of porous media* Transactions AIME 1951

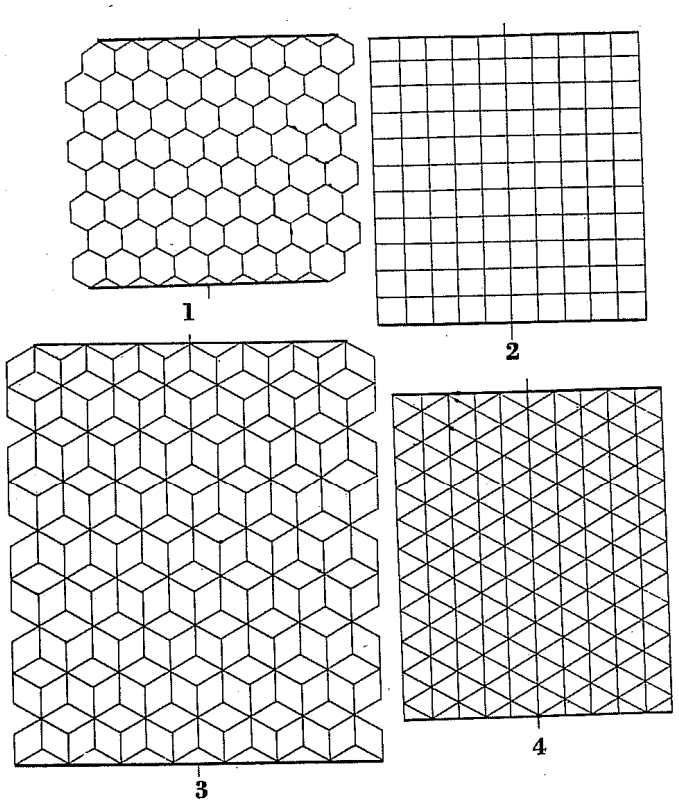
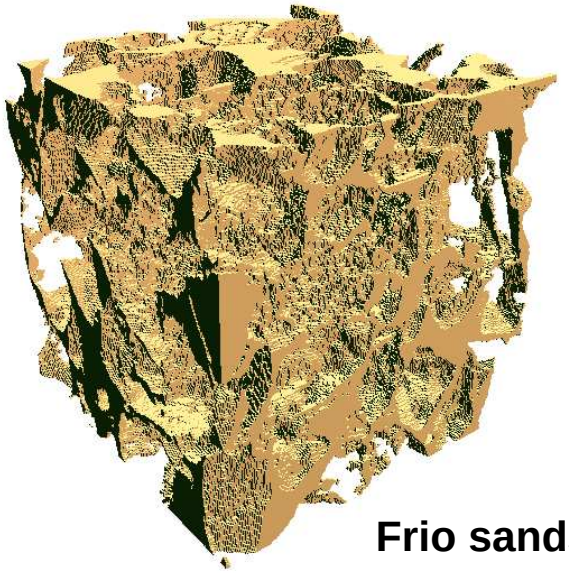


FIG. 1—SINGLE HEXAGONAL NETWORK.
FIG. 2—SQUARE NETWORK.
FIG. 3—DOUBLE HEXAGONAL NETWORK.
FIG. 4—TRIPLE HEXAGONAL NETWORK.

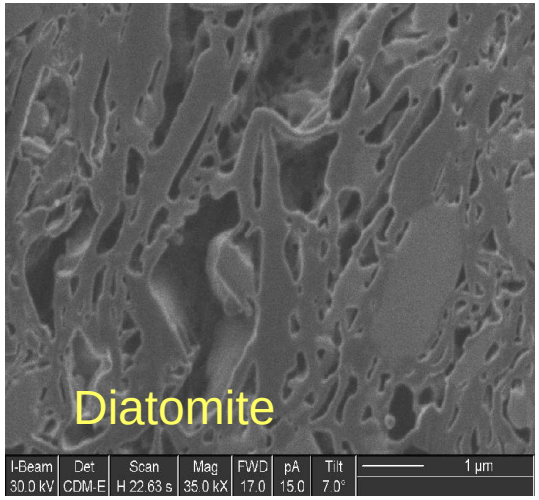
New opportunities

3D reconstruction of the pore space

- X-ray computer tomography (CT): micron-scale resolution
- Focused-ion-beam (FIB): nanometer scale
- Computing power



Frio sandstone

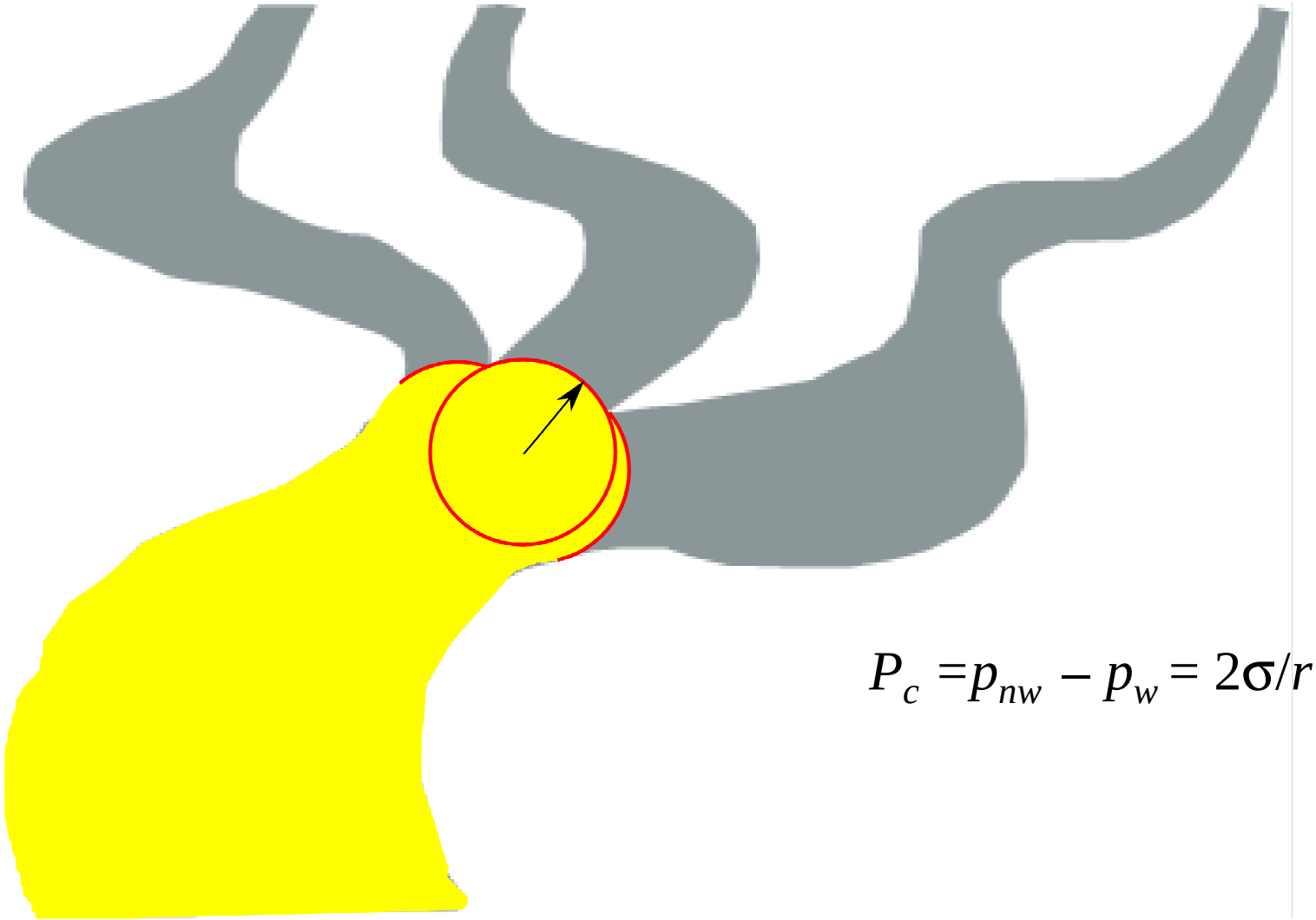


Micro CT and SEM: Liviu Tomutsa, LBNL

Outline

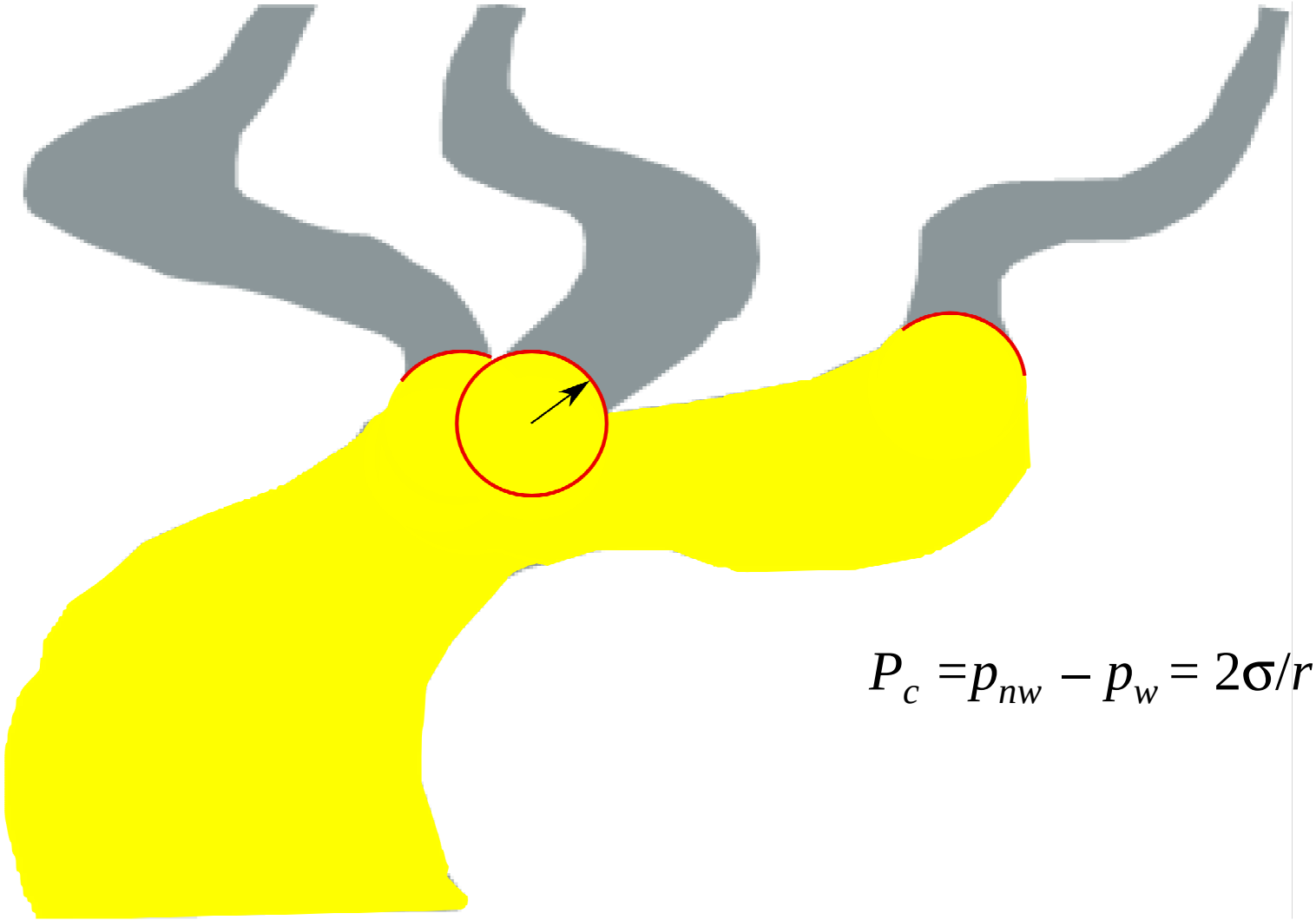
- Maximal Inscribed Spheres method
  - Capillary equilibrium
  - Verification
- Solving flow equations
  - The method of artificial compressibility
  - The curse of dimensionality: domain partitioning
- Relative permeability curves

Maximal inscribed spheres: fluid distribution



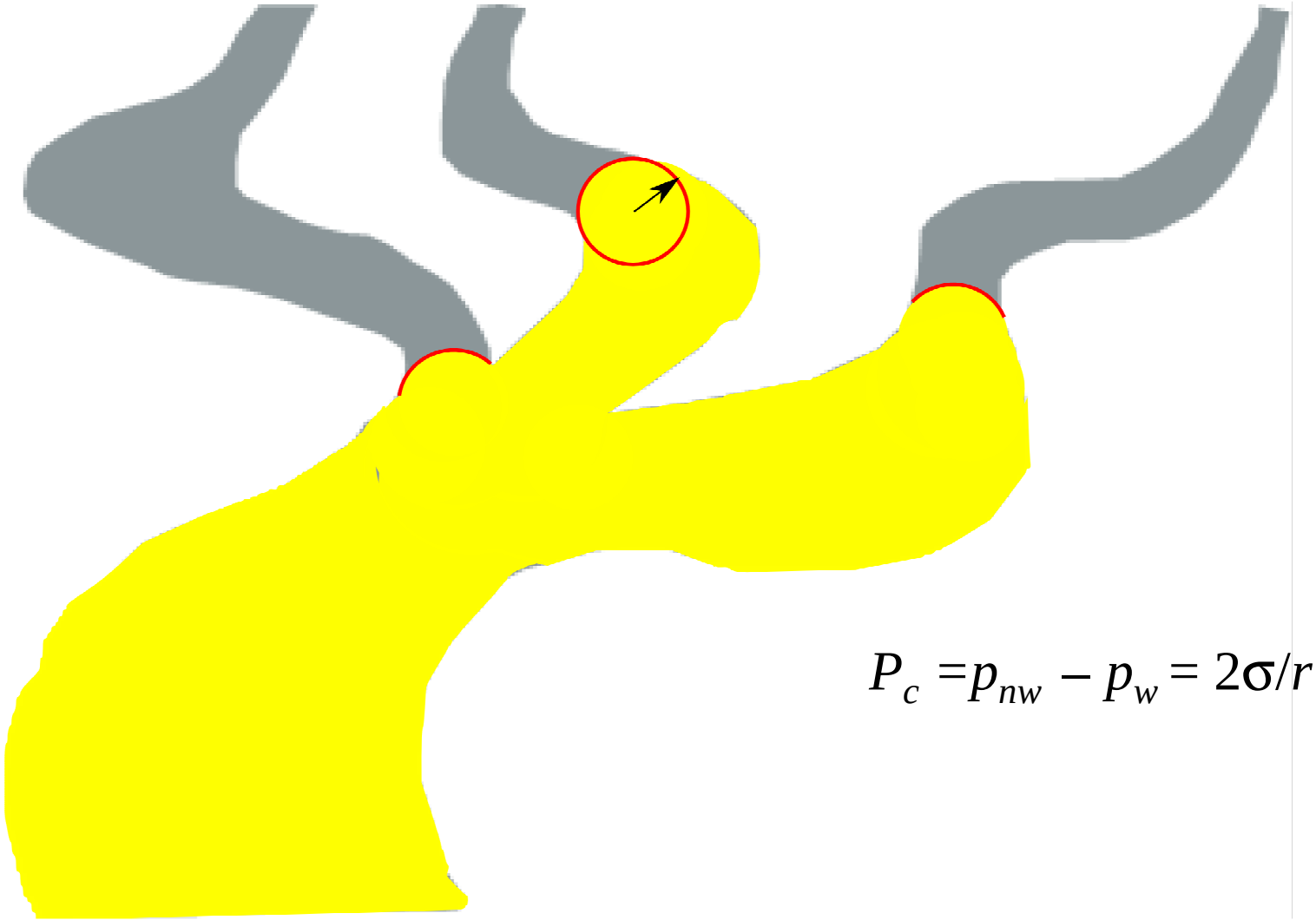
$$P_c = p_{nw} - p_w = 2\sigma/r$$

Maximal inscribed spheres: fluid distribution



$$P_c = p_{nw} - p_w = 2\sigma/r$$

Maximal inscribed spheres: fluid distribution



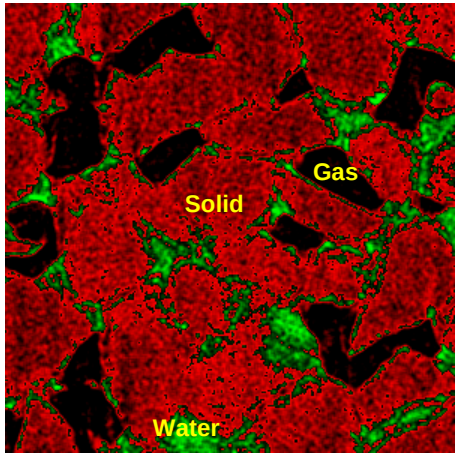
$$P_c = p_{nw} - p_w = 2\sigma/r$$

Maximal inscribed spheres

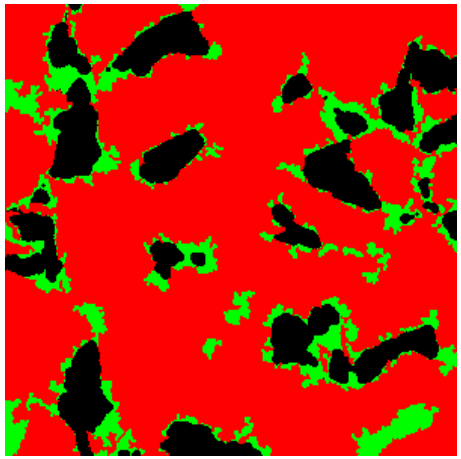
- Assumptions
  - Capillary equilibrium
  - Disperse saturation is negligible
- Implementation
  - Input: 3d binary image of the pore space
  - 3D maximal radii table
  - Connectivity: cluster search
  - Large input data sets

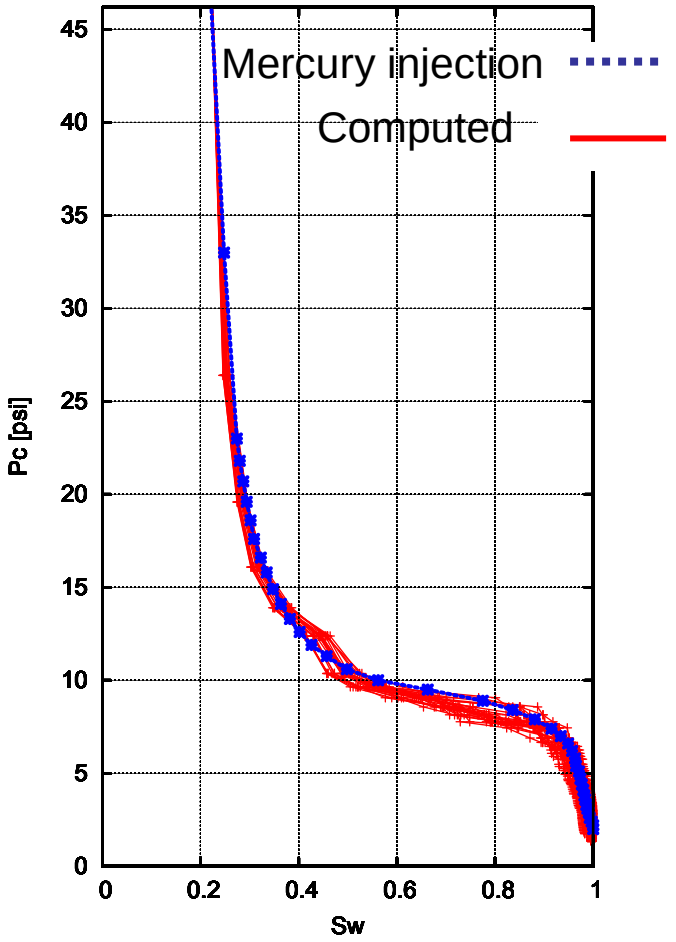
Maximal inscribed spheres: verification

CT image



MIS Calculations





Silin, D., Tomutsa, L., Benson, S M., Patzek, T W.
Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract H12C-07, 2008

The method of artificial compressibility

A.Chorin: Journal of Computational Physics 1967

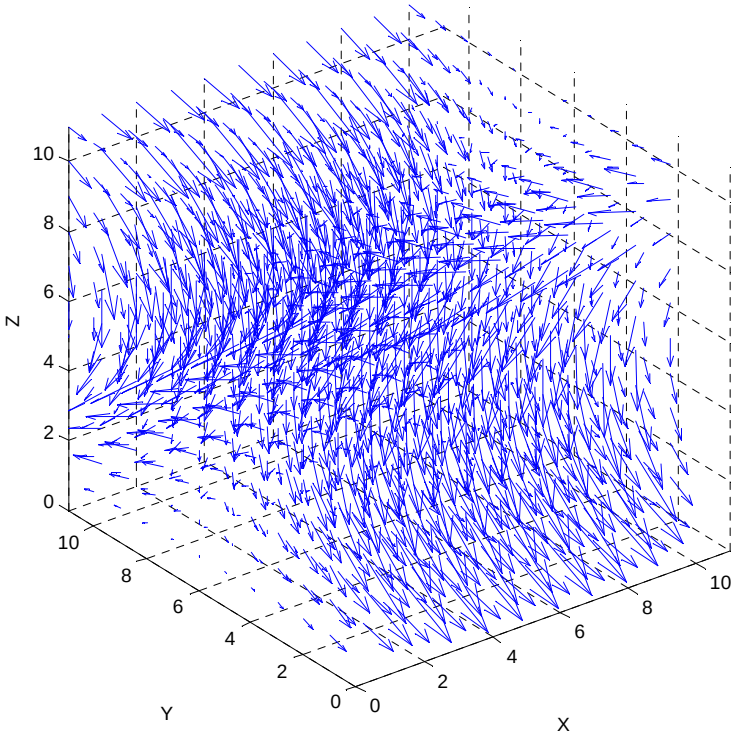
$$\frac{\partial}{\partial t}\mathbf{v} + \mathrm{Re}(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p + \nabla^2\mathbf{v}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\mathbf{v} = 0$$

$$\rho = \delta p$$

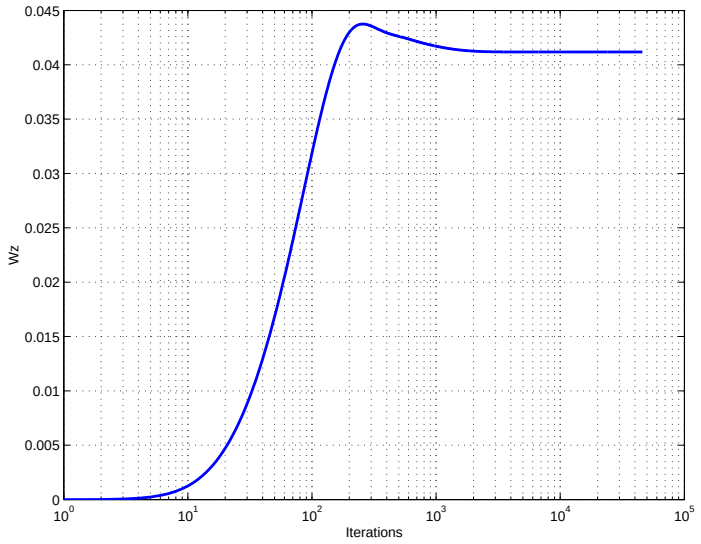
Computational parameters:

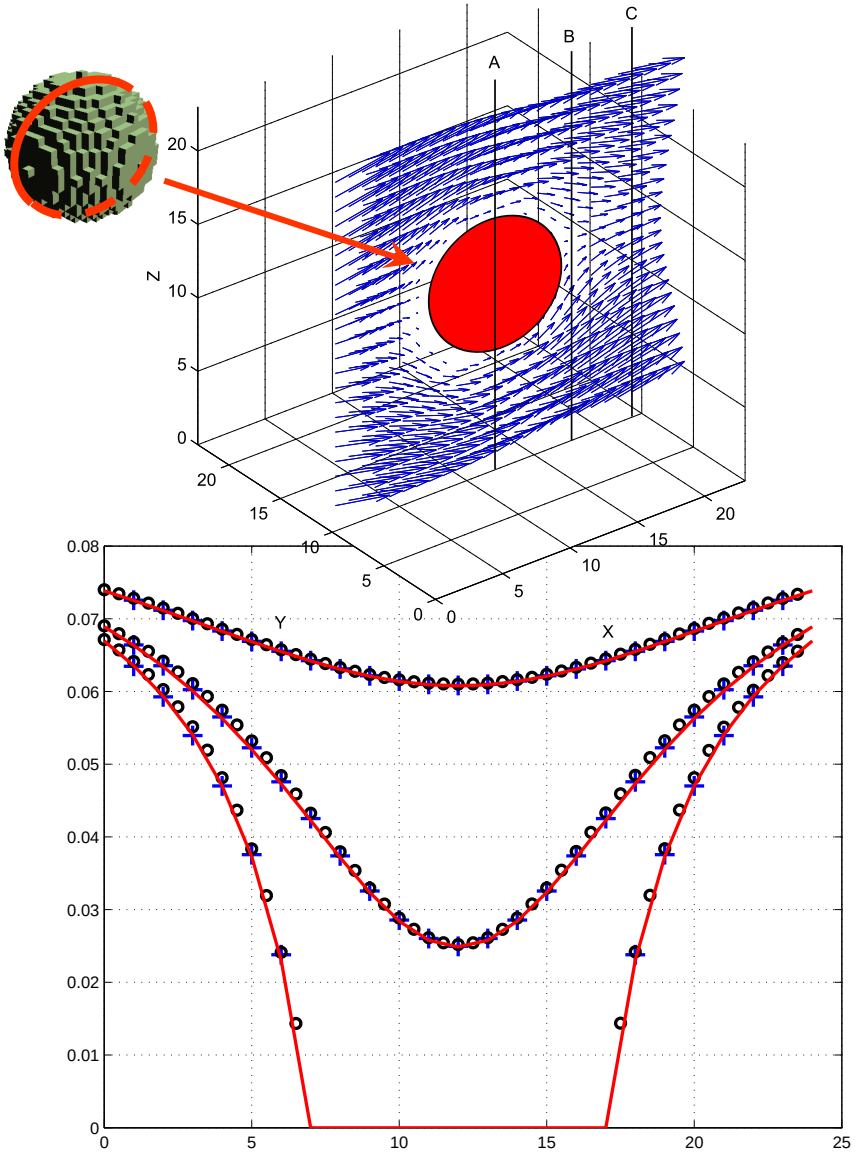
- iteration parameter
- artificial density
- artificial compressibility



Example: Stokes flow

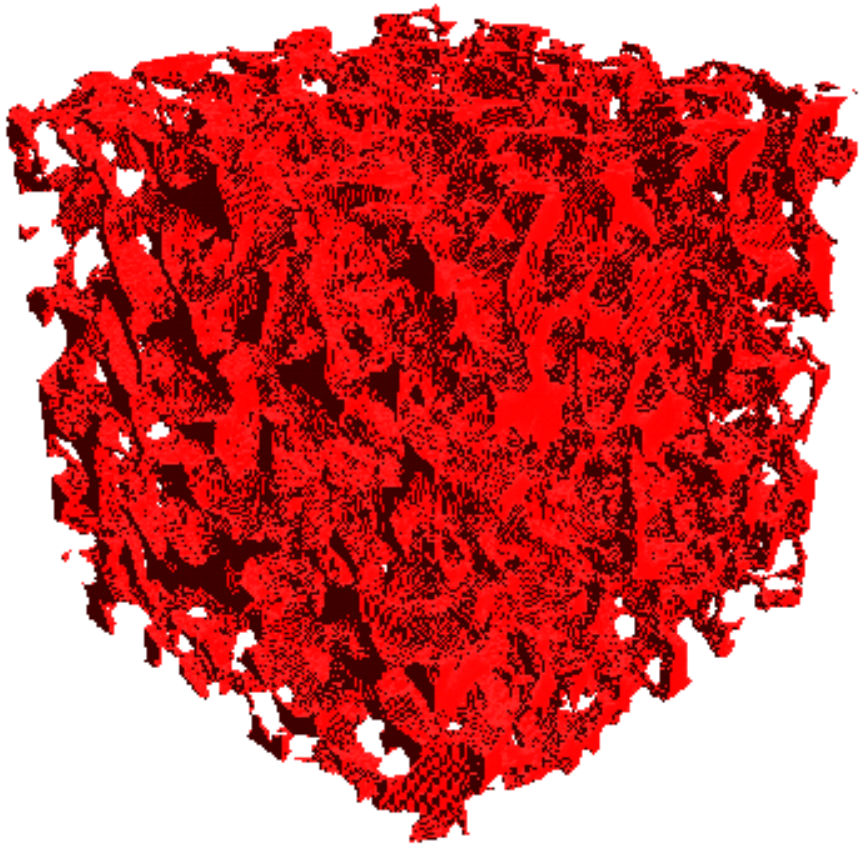
- Convergence is critically important for estimation of Darcy velocity
- A severe criterion must be imposed



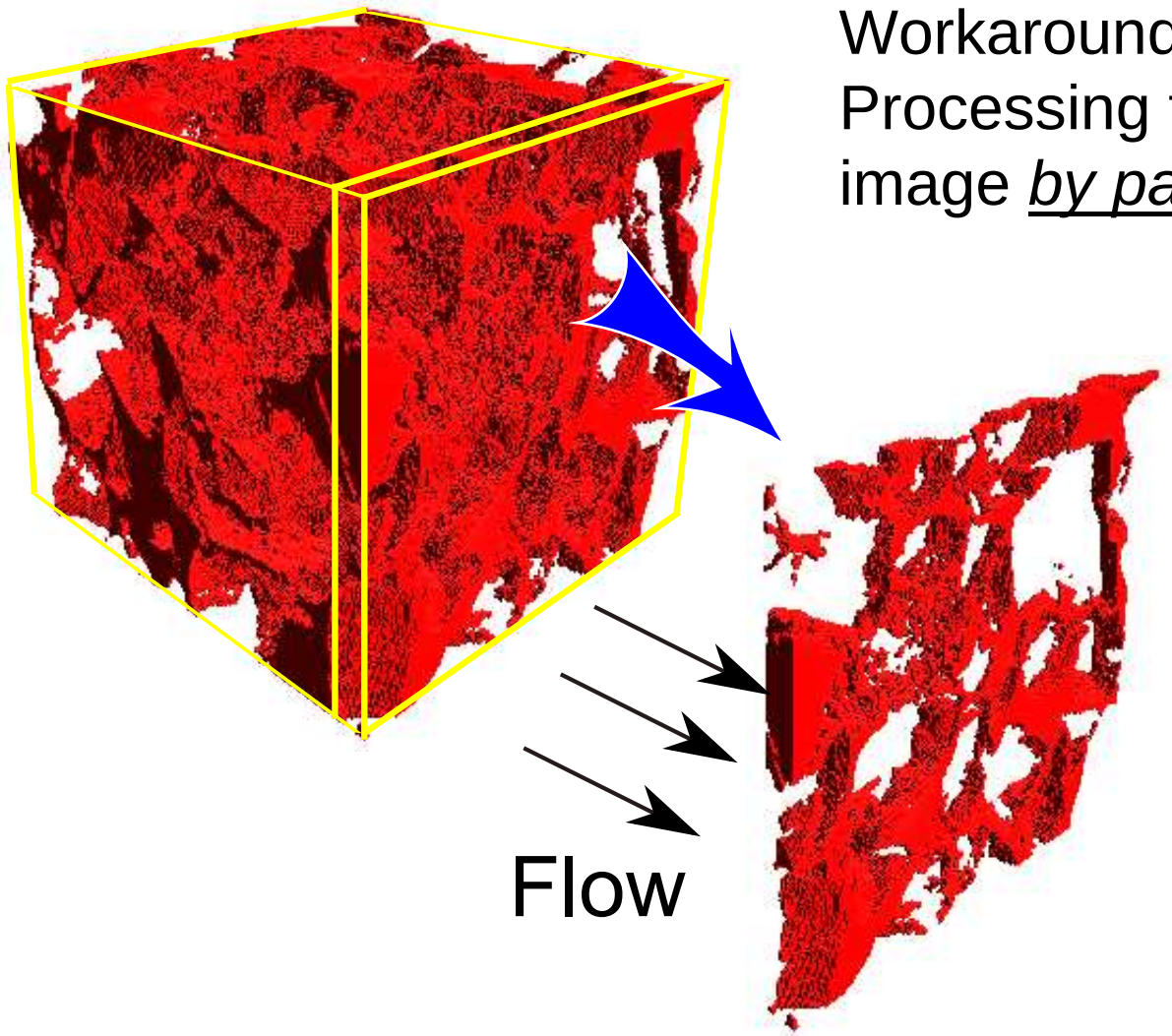


“The Curse of Dimensionality”

- Good news:
  - High-resolution images → accurate discretization
- Bad news:
  - 5mm×5mm×5mm at 5 micron resolution = 1GB
  - Millions of grid cells → enormous volume of computations



Slicing the whole sample into layers

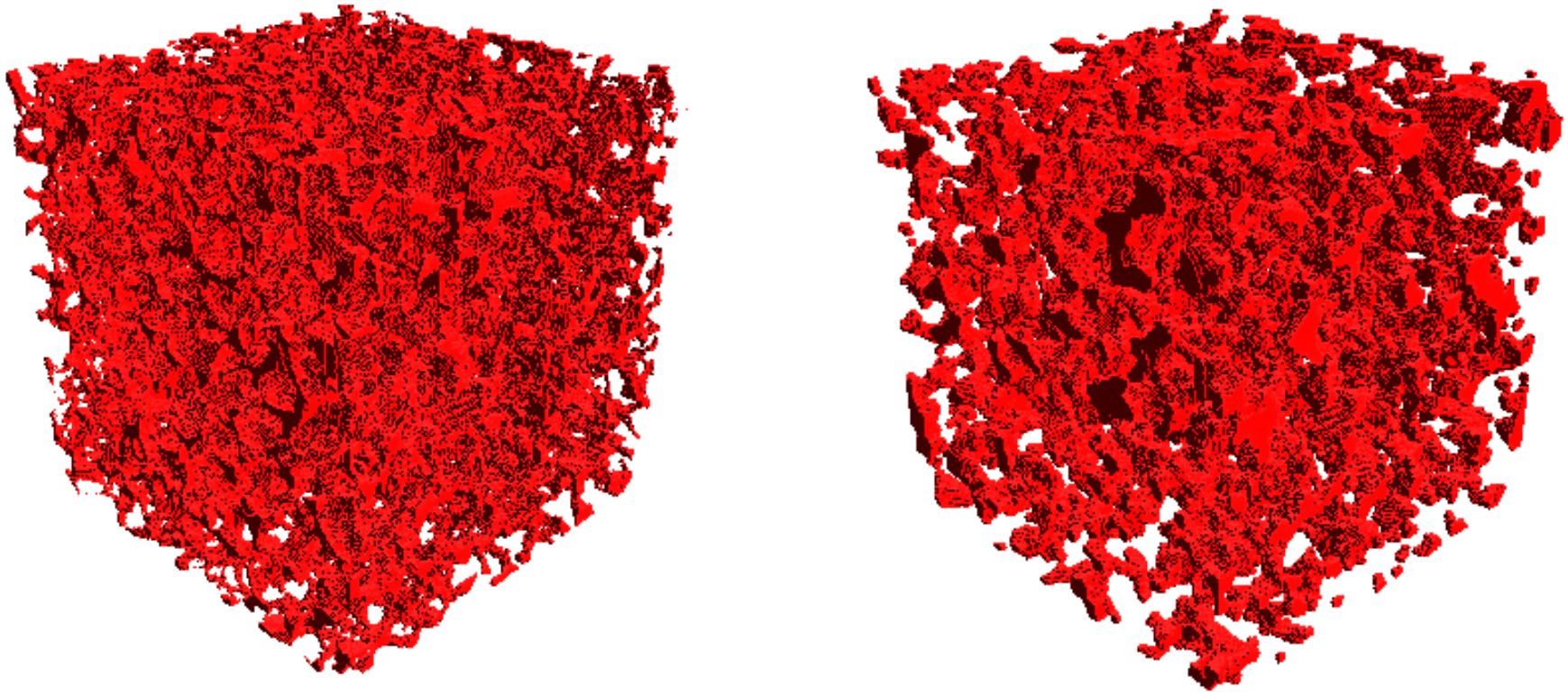


Workaround:
Processing the whole image *by parts*

Evaluation of relative permeability curves

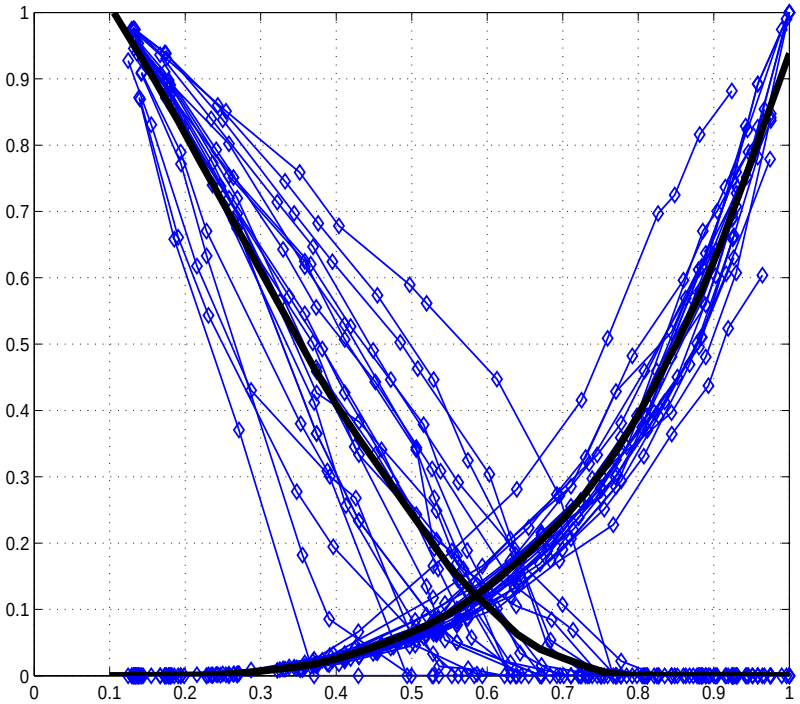
Wetting fluid

Non-wetting fluid



MIS-calculated fluid distribution

Relative permeability evalculation



MIS-calculations

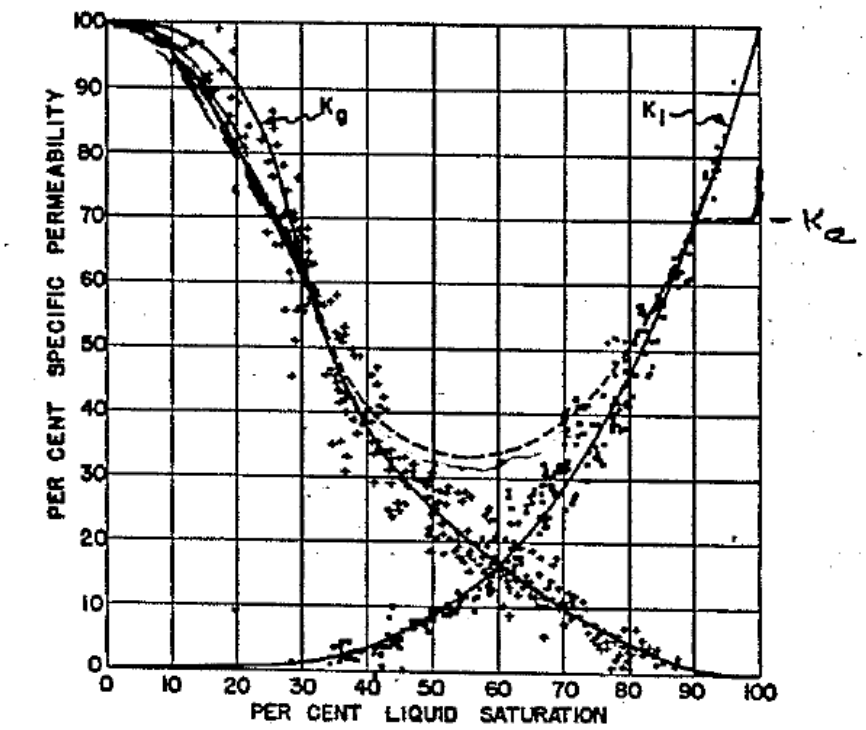


FIG. 9. Composite curves showing permeability-saturation data for all four sands.

Wyckoff & Botset 1936

Summary and conclusions
MIS-calculations + FD simulations:

- Benefits:
  - Partitioning of a large sample $\rightarrow$ distributed computations
  - Analysis of the digital image bypassing pore network extraction
  - Large high-resolution images can be processed on a desktop computer
- Weaknesses
  - Severe criterion for convergence
  - “The curse of dimensionality”
- A promising approach for routine applications
- Generalizations
  - Modeling of the impact of mechanical deformation, mineralization, etc

Acknowledgments

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